Comparative Analysis of Double Stator Permanent Magnet Flux-Switching Machines with Segmented Inner Stator and Non-Segmented Inner Stator

S. Khalidah, M. Z. Ahmad, Gadafi M. Romalan and M. Z. Md Arap
Research Centre for Applied Electromagnetics (EMC), Faculty of Electrical & Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Johor, Malaysia
sitikhalidah17@gmail.com

***Abstract*—This paper examines and compares the analysis of double stator PMFSM between segmented and non-segmented inner stator. The analysis particularly focused on output performance of flux linkage, back-EMF, cogging torque, average torque at various armature current densities, speed and power characteristics which are investigated using JMAG-Designer ver. 14.0. The aim of analysis is to overview the suitable design for future electric transportation based on the characteristic of double stator PMFSM. Thus, the 2D finite element analysis (FEA) approach is used for preliminary analysis. Based on flux linkage analysis, the segmented design generates higher magnetic flux magnitude which is 40% higher than the non-segmented design. Moreover, the segmented design also achieved higher torque and power compared to the non-segmented design with 35.54% and 32.06% different percentage, respectively. The results obtained show that the segmented design produces better performance compared to non-segmented in terms of torque and power.**

***Index Terms*—Double Stator; Flux-Switching; Permanent Magnet; Partitioned Stator.**

I. INTRODUCTION

In recent years, the usage of electrical motors is attractively developed by the industrial motor manufacturer for industrial and transportation purposes. Production of electric motors for transportations increased compared with vehicles that applied internal combustion engine motor. It is due to the internal combustion engine motor creates pollution that harmful to the environment compared with electric vehicle. The specification of the electric motor in terms of power rating, size and output torque must be suitable and meet the requirement of electric vehicles [1]-[4].

Nowadays, permanent magnet flux switching motors (PMFSMs) become an attractive research topic for electric vehicle applications due to their advantages of high torque and power densities capabilities [5]-[8]. In order to increase the torque density, several researchers proposed partitioned stator or double stator. The partitioned stator or double stator basically split the motor stator into two different stators namely PMs and armature stator.

As compared with the conventional PMFSM, the design of double stator PMFSM has such benefits which are the increase of the torque density since the permanent magnet (PM) and armature coils are no longer crowded in one stator [5]. The design also eventually increased the torque density due to higher utilization of the inner space of the motor.

Thus the double stator PMFSM with segmented is designed to increase the torque density applying conventional PMFSM. However, due to inner stator structure machine is constructed of segmented structure, the stator is difficult to be fabricated and the structure is less robust [1]. Furthermore, a large amount of the excitation sources on the stator will limit the armature coil area and lead to poor thermal dissipation condition and low torque density [1]-[2]. Consequently, the machine becomes inappropriate for high-speed application. Therefore, the double stator PMFSM with non-segmented inner stator is proposed to eliminate the segmented issues. With simple structure which is more robust and easy to fabricate, the output performance is compared with the segmented design.

II. ANALYSIS APPROACH

Figure 1 illustrates the workflow or the analysis approach for comparative analysis of double stator permanent magnet flux-switching machines (DS-PMFSM). The conventional PMFSM structure [11] is adopted into the new DS-PMFSM for further investigation. The approach used JMAG Geometry and Designer in design and analyzed the design based on 2D FEA. Thus the outcome of the 2D FEA is collected and compared to determine the best structure for future investigation.

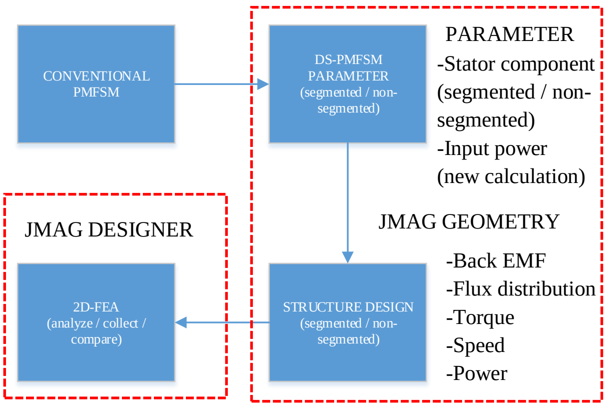
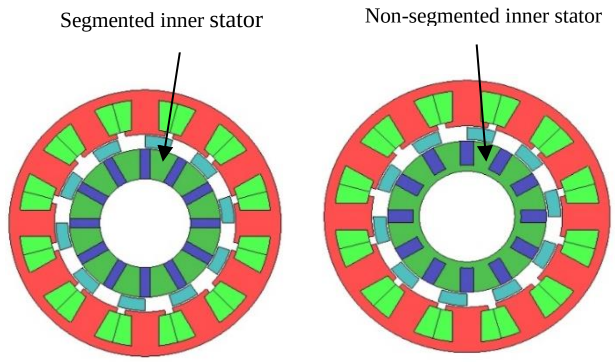


Figure 1: Workflow analysis approach

III. MACHINE STRUCTURE

As depicted in analysis approach workflow, the DS-PMFSM is design used JMAG Geometry based on fundamental of conventional PMFSM. However, the design is improved by double the stator component. Theoretically, by double the stator, the excitation component also increase. In which the machine capable to deliver more power while increasing the machine performance itself. Thus the design slightly differs with the conventional PMFSM.

Figure 2(a) and 2(b) show double stator PMFSM machines with the segmented inner stator and non-segmented inner stator, respectively. Both designs consist 10 rotor pole slot and 12 stator pole slot. Simultaneously, Figure 2 shows the difference between segmented and non-segmented structure, in which the non-segmented structure show short permanent magnet is used to eliminate the segmented issues for DS-PMFSM. The machine parameters for both designs are presented in Table I.



(a) (b)

Figure 2: Cross-sections of Double Stator PMFSM; (a) Segmented inner stator, (b) Non-segmented inner stator

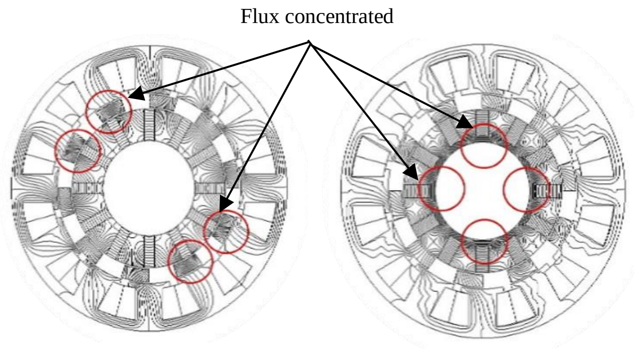
Table 1
Parameters of DS-PMFSM

Parameter	DS-PMFSM with segmented inner stator	DS-PMFSM with non-segmented inner stator
Number of PMs	12	
Stator pole number	10	
Rotor pole number	400	
Stator outer radius (mm)	45	
Stator inner radius (mm)	15	
Axial length (mm)	25	
Air-gap length (mm)	0.5	
Armature stator axial length (mm)	10	
Armature stator back-iron thickness (mm)	3.33	
Excitation stator axial length (mm)	10	
Excitation stator back-iron thickness (mm)	6.67	
Rotor axial length (mm)	4	
Number of turns of armature coil	20	
PM thickness	3.33	4.16625
PM length	10	8
Filling factor	0.6	

IV. Electromagnetic Performance

A. Open-Circuit Performance

The open-circuit analysis requires non-load is assigned during the preliminary setup. This type of setup is needed for the preliminary test in ensuring the motor fundamental is same as fundamental theory and to determine the zero rotor position. From the analysis, the flux line of segmented and non-segmented inner stator is demonstrated in Figure 3(a) and 3(b) after complete one cycle flux, respectively. As illustrated, the flux line flow from the inner stator to the rotor and switch with permanent magnet (PM) flux, while the outer stator flux flow also behaves the same. As shown in Figure 3, the flux line concentrated at the rotor for segmented design while for the non-segmented, the flux is concentrated at the inner stator bridge. This happened due to increasing core area with help of reducing PM length.

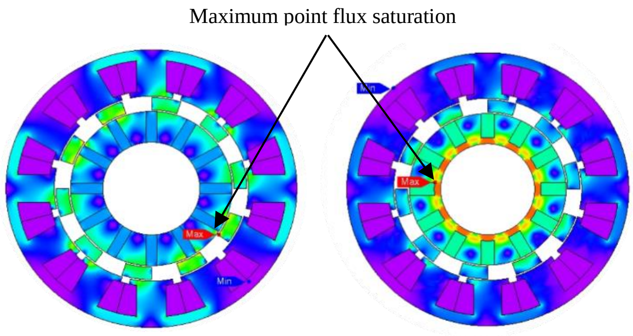


(a) (b)

Figure 3: Flux Line of Double Stator PMFSM (a) Segmented inner stator (b) Non-segmented inner stator

Meanwhile, Figure 4(a) and 4(b) shows the magnetic flux distribution of both designs. The distribution flux is different due to the structure and PM strength factor. The depicted magnetic flux in Figure 4 shows the minimum and maximum point flux saturation in which the point of saturation is same as illustrated in flux line concentrated.

The maximum point saturation magnetic flux density for the segmented design is less than the non-segmented design with 1.9T and 2.09T, respectively. This happened due to the PM has been reduced which effect the excitation strength and simultaneously affect the intensity changes of flux distribution.



(a) (b)

Figure 4: Flux distribution of double stator PMFSM
(a) Segmented inner stator (b) Non-segmented inner stator

The magnetic flux can be visualized in the graph of phase flux linkage that been shown in Figure 5. Based on u-phase linkage analysis of both motor in Figure 5, it shows the double stator PMFSM with the segmented structure of inner stator has the higher magnetic flux which is approximately 0.01Wb compared with the magnetic flux of double stator with the non-segmented structure of inner stator which is approximately 0.006Wb. There is percentage difference of 40% when both motors are being compared. It is due to the effect of the permanent magnet that being shortened by 2mm for double stator PMFSM with the non-segmented inner stator.

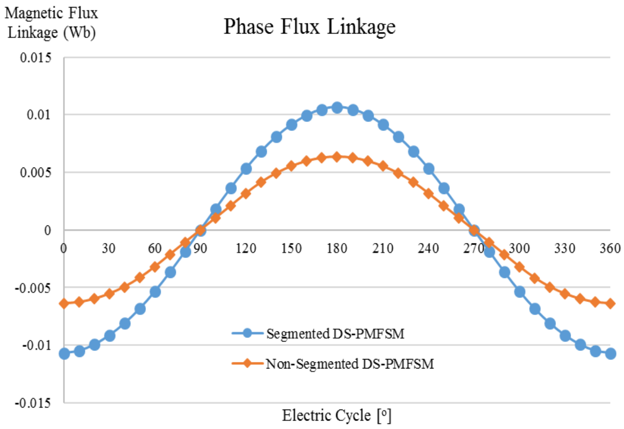


Figure 5: Phase flux linkage comparison

Next, the phase back-EMF of double stator PMFSM with the segmented inner stator and double stator PMFSM with non-segmented inner stator been analyzed as shown in Figure 6. The induced voltage, also known as back-electromotive force (EMF) is analysed at the rated speed of 400rpm. Based on Figure 6, the amplitude of fundamental component is approximately 8V for the double stator PMFSM with segmented inner stator while the amplitude of fundamental component for double stator PMFSM with non-segmented inner stator is approximately 4.5V.

As referring to Figure 6, it is clearly shown that the amplitude of back-EMF for the non-segmented inner stator of double stator PMFSM significantly has lower back-EMF with a percentage difference of 43.75% for both motors. In addition, the back-EMF for the segmented inner stator of double stator PMFSM looks more sinusoidal compared with the non-segmented inner stator of double stator PMFSM. It is due the presence of harmonics occurred in the non-segmented inner stator of double stator PMFSM compared with the segmented inner stator of double stator PMFSM.

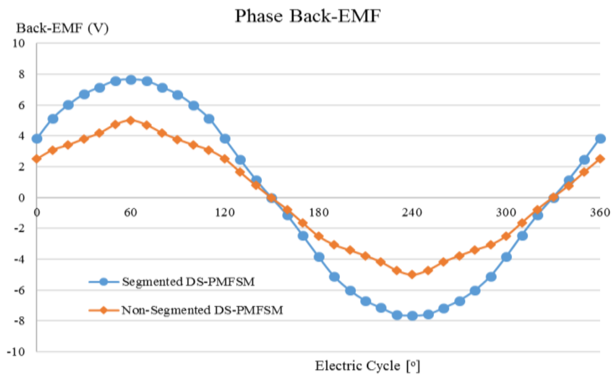


Figure 6: Phase back-EMF at rated speed 400rpm

The cogging torque profile of the DS-PMFSM with segmented inner stator and non-segmented inner stator illustrated in Figure 7. Cogging torque is a torque due to the interaction between the permanent magnet (PM) and the stator within the un-energized motor. Cogging torque is also known as 'no-current' torque. Obviously, six cycles of cogging torque are generated in one electric cycle. In Figure 7 shows the peak-peak cogging torque of PM only is approximately 0.4258Nm for double stator PMFSM with segmented inner stator while the peak-peak cogging torque of PM only in double stator PMFSM with non-segmented inner stator is approximately 0.119676Nm.

It shows that the double stator PMFSM with segmented inner stator has low cogging torque compared with the double stator PMFSM with non-segmented inner stator cogging torque. Based on this analysis, the low cogging torque considered better performance as the cogging torque is an undesirable component for the operation of such a motor, especially in DS-PMFSM analysis.

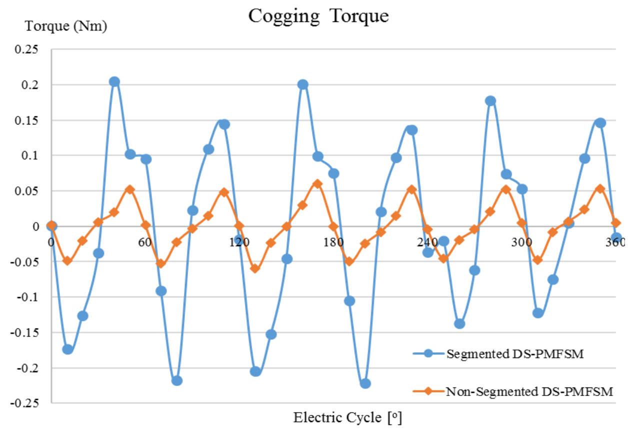


Figure 7: Comparison of cogging torque margin

B. *On-load Performance*

Figure 8 illustrates the graph torque and armature current density, J_A. During the load test, the armature current density, J_A varied from 0 to 20. The torque obtained for both of the motor design increased as the armature current, J_A being increased. For the torque versus armature current density, J_A, the value of armature current, I_A of each armature current density, J_A needs to be found by using the equation 1. Next, the peak current, I_{peak} need to be found by using equation 3 based on the armature current obtained in Equation 1.

$$N_A = \frac{J_A \alpha \, S_A}{I_A} \tag{1}$$

where: I_A = Input current
N_A = Number of turn
J_A = Current density
S_A = Slot area
α = Filling factor

From Equation 1, the armature current is determined. Note that the filling factor, armature current density and number of turn is set 0.5, 0-20A_{rms}/mm^2 and 20, respectively. While the slot area is based on the parameters in Table 1. Table 2 present the calculated value of armature current used in this analysis.

Based on Figure 8, the double stator PMFSM with segmented inner stator has higher torque obtained which is 5.12Nm compared with double stator PMFSM with non-segmented inner stator torque obtained which is 3.29Nm.The percentage difference between maximum torques for both of the motor is 35.74%.

Table 2
Value of Armature Current, i_a

Armature Current Density, J_A	I_A / I_{rms} (A)	I_{peak} / J_{max} (A)
0	0	0
5	6.25	8.8388
10	12.5	17.677
15	18.75	26.516
20	25	35.355

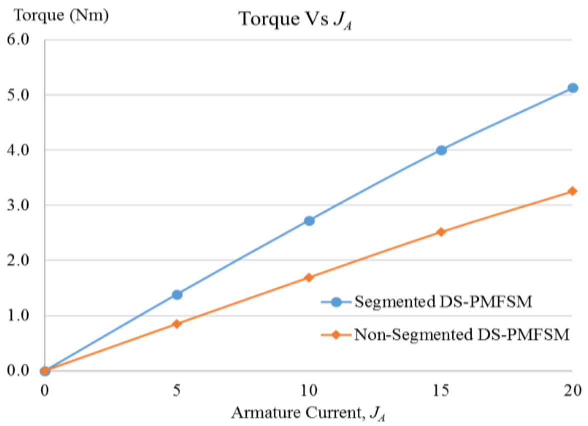


Figure 8: Torque (Nm) versus Armature Current Density, J_A

The torque and power versus speed curves of the both of the motor are presented in Figure 9. Double stator PMFSM with segmented inner stator portrays higher torque and power performance which torque obtained is 5.12968Nm, as the maximum at the base speed of 1370.63r/min, and the corresponding power reaches 736.25W, respectively, compared with the double stator PMFSM with segmented inner stator, the double stator with non-segmented inner stator results the maximum torque obtained is 3.30Nm, as the base speed of the motor is 1444.34r/min, and the corresponding maximum power reaches 514W, respectively. The simulation results showed percentage difference of output performance between both motors for torque characteristics is 35.54% and for power characteristics is 32.06%.

As a comparison, the double stator PMFSM with segmented inner stator results in the higher output torque and power performance compared with double stator PMFSM with the non-segmented inner stator. However, the double stator PMFSM with non-segmented inner stator shows better performance in cogging torque analysis.

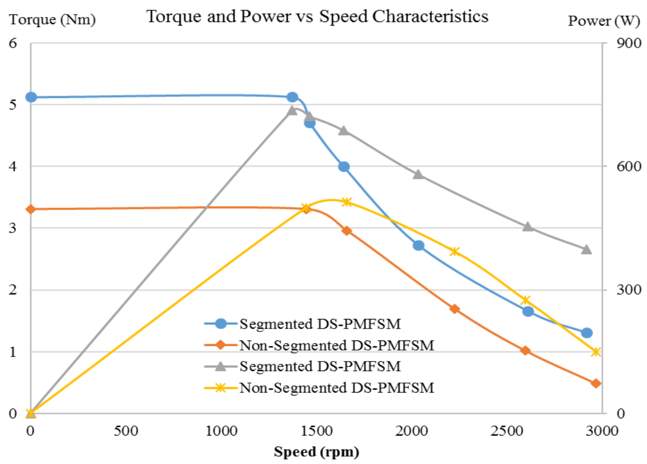


Figure 9: Torque (Nm) and Power (W) versus Speed (r/min) Characteristics

V. Conclusion

In this paper, the analysis of double stator PMFSM with the segmented inner stator and non-segmented inner stator has been presented. Based on the overall output performance of the double stator PMFSM with the segmented inner stator and the double stator with the non-segmented inner stator, the analysis results show the DS- PMFSM with segmented has higher output performance compared with double stator PMFSM with the non-segmented inner stator in various aspect. The results concluded the motor can be designed in a simpler structure. Thus, the motor is easy to fabricate compared with the segmented structure. However, the result analysis shows the non-segmented structure has lower output torque and power performance when compared with the segmented inner stator of DS-PMFSM. In order to realize the non-segmented design benefit, the optimization process should be carried out to improve the output torque and power performance of the DS-PMFSM.

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